EZ Lidar™: A new compact autonomous eye-safe scanning aerosol Lidar for extinction measurements and PBL height detection. Validation of the performances against other instruments and intercomparison campaigns

S. Lolli, L. Sauvage, S. Loaec, M. Lardier

Sección Especial / Special Section: V Workshop on Lidar Measurements in Latin America

EZ Lidar™: A new compact autonomous eye-safe scanning aerosol Lidar for extinction measurements and PBL height detection. Validation of the performances against other instruments and intercomparison campaigns

S. Lolli[1,2,*], L. Sauvage[1], S. Loaec[1], M. Lardier[1]

1. Leosphere, 76 Rue Monceau 75008 Paris, France.
2. LMD(Laboratoire de Meteorologie Dynamique), Ecole Polytechnique, Palaiseau, France.

[*] Email: slolli@leosphere.fr S: miembro de SEDOPTICA / SEDOPTICA member

Recibido / Received: 16/11/2010. Versión revisada / revised versión: 10/01/2011. Aceptado / Accepted: 11/01/2011

ABSTRACT:

A compact and rugged eye safe UV Lidar, the EZ Lidar™, has been developed by LEOSPHERE (France) to study and investigate structural and optical properties of clouds and aerosols continuously, thanks to the strong know-how in the field of air quality measurements and cloud observation and analysis. EZ Lidar™ has been validated by different remote or in-situ instruments as Micropulse Type-4 Lidar or the Lidar Nuages Aérosols (LNA) at the Laboratoire de Metereologie Dynamique (LMD), in France and in several intercomparison campaigns (LISAIR'05, AMMA ASTAR/IPY TIGERZ'08, and ICOS). Outdoor and unattended use capabilities of the EZ Lidar™ added to its measurements performances define then this instrument as a good candidate for deployment into growing global aerosol and cloud monitoring networks and research measurement campaigns.

Key words: Lidar, Atmospheric Aerosols , Dust Transport, Extinction.

REFERENCES AND LINKS

[1] J. D. Klett, "Stable analytical inversion solution for processing lidar returns", *Appl. Opt.* **20**, 211-220 (1981).

[2] R. B. Stull, *An Introduction to Boundary Layer Meteorology*, Kluwer Academic Publishers, Dordrecht (1988).

[3] S. Lolli, "EZ Lidar uncertainty analysis in AOD retrievals", LEOSPHERE internal communications (2008).

[4] A. Ansman, M. Riebesell, C. Weitkamp, "Measurements of atmospheric aerosol extinction profiles with Raman lidar", *Opt. Lett.* **15**, 746-748 (1990).

[5] J. R., Campbell, D. L. Hlavka, E. J. Welton, C. J. Flynn, D. D. Turner J. D. Spinhirne, V. S. Scott, I. H. Hwang, "Full-time,eye-safe cloud and aerosol lidar observation at Atmospheric Radiation Measurement Program sites: Instrument and data processing", *J. Atmos. Ocean. Tech.* **19**, 431–442 (2002).

[6] Y. Morille, M. Haeffelin, P. Drobinsky, J.Pelon, "STRAT: an automated algorithm to retrieve the vertical structure of the atmosphere from single channel lidar data", *J. Atmos. Ocean. Tech.* **24**, 761–775 (2007).

[7] R. A. Ferrare, D. D. Turner, L. H. Brasseur, W. F. Feltz, O. Dubovik, T. P. Tooman, "Raman lidar measurements of the aerosol extinction-to-backscatter ratio over the Southern Great Plains", *J. Geophys. Res.* **106**, 20333–20347 (2001).

1. Introduction

Aerosols influence climate through different pathways, directly on the scattering and absorption of radiation, indirectly on the processes of cloud formation and microphysics. Monitoring the global distribution of aerosols requires continuous observations both from ground based networks and from satellite platforms. In this way is possible to better understand the Earth climate changes especially in order to slow the global warming and controlling the emissions of light-absorbing particles. For this reason, Lidars are widely used to determine the vertical and horizontal distribution of clouds and aerosols. The EZ Lidar™ is a small, autonomous rugged eye-safe instrument used for continuous observations that has been validated by different remote or in-situ instruments as Micropulse Type-4 Lidar manufactured by NASA at ARM/SGP site or the Lidar Nuages Aérosols (LNA) at the Laboratoire de Metereologie Dynamique (LMD), in France and in several intercomparison campaigns. Further EZ Lidar™ was deployed in different air quality and long distance aerosol transport research campaigns (LISAIR'05, AMMA Niger campaign in January 2006, ASTAR/IPY in April 2006, TIGERZ'08 together with NASA / AERONET, ICOS).

2. EZ Lidar™ instrument

EZ Lidar™ is a ground-based optical remote sensing instrument designed to determine the vertical and horizontal properties of the atmosphere. The physical principle is the same as for radar: a short pulse of laser light is transmitted from the telescope to the atmosphere. As the pulse travels along, part of it is scattered by molecules, anthropogenic particles, water droplets, or other objects in the atmosphere. The greater the number of scatterers, the greater the part scattered. A small portion of the scattered light is scattered back, collected by the telescope, and detected. The detected signal is stored in bins according to how long it has been since the pulse was transmitted, which is directly related to how far away the backscatter occurred. The collection of bins for each pulse is called a profile. A bigger concentration in aerosol will be evident as an increase or spike in the back-scattered signal profile, since, for example, the water droplets that make up the cloud will produce a lot of backscatter. Moreover, the depolarization detection channel gives asphericity information on the particle in order to discriminate some particles from others (soil dust from other aerosol, ice/water phase of the clouds…).

The EZ Lidar™ uses a tripled pulse laser source ND: YAG at 355 nm wavelength with energy of 16mJ and pulse duration of 7 ns and repetition frequency of 20 Hz. Both analog and photon counting detections are available. The Lidar system provides a real time measurement of backscattering and extinction coefficients, Aerosol Optical Depth (AOD), automatic detection of the Planetary Boundary Layer (PBL) height, depolarization ratio, and clouds base and top height from 50 m up to 20 km. In Table I are schematically reported the instrument characteristics.

Table I

EZ Lidar™ technical characteristics

Range	50 m–20 km
Temporal Resolution	1s(PBL)/30s
Spatial Resolution	1.5m/15m
Angular Resolution	0.2º
Scanning Speed	8º/s
Environment	–20ºC/+50ºC
Humidity	0-100%
Waterproofing	IP65
Weight	~48 kg
Eye Safety	IEC60825-1 2001

In elastic single scattering conditions, from the Lidar equation, the EZ Lidar™ count rate is:

$$P(z)=\frac{CEO(z)[\beta_M(z)+\beta_P(z)]T_M^2(z)T_P^2(z)}{z^2}+B_{bkg}=$$
$$=P_{Raw}(z)+B_{bkg}\,, \quad (1)$$

where $P(z)$ is the measured signal (photoelectrons/ns per shot) at range z, C represents the dimensional system calibration constant, E is the pulse energy, $O(z)$ is the overlap correction as a function of range caused by field of view conflicts in the transmitter-receiver system, $\beta_M(z)$, $\beta_P(z)$ are the molecular and particle backscattering coefficients, T_M^2, T_P^2 are respectively the molecular and particle atmospheric transmittances:

$$T_{M,P}^2(z) = \exp\left\{-2\int_0^z \alpha_{M,P}(z')dz'\right\}, \qquad (2)$$

with $\alpha_{M,P}(z)$ being respectively the molecular and particle extinction coefficients and B_{bkg} is the flux of photoelectrons due to the solar background. If we remove from Eq. (1) all instrument parameters except the calibration constant, and subtract the background contribution, it is possible to define the resulting signal from the correction as the Normalized Relative Backscattering (NRB):

$$P_{NRB}(z) = C[\beta_M(z) + \beta_P(z)]T_M^2(z)T_P^2(z). \qquad (3)$$

The NRB signal is significant because it is dependent on atmospheric parameters and only one instrument parameter, C. The NRB signals are used to provide information on the vertical and horizontal structure of aerosols and clouds, and also to solve for aerosol extinction profiles.
The uncertainty in the NRB signals is required to assess the accuracy of aerosol and cloud heights identified from the signals, as well as extinction, backscattering and relative AOD profiles and values calculated from them.

From Klett algorithm [1], the retrieved total backscattering is function of:

$$\beta_{tot}(z) = f[P_{NRB}(z), L_R, \beta_M(z)]. \qquad (4)$$

where $P_{NRB}(z)$ is the previously described normalized relative backscatter (3), L_R is the Lidar Ratio, an input parameter required from inversion Klett algorithm defined as the ratio of the particulate extinction to backscattering. It presupposes the knowledge of the aerosol types in the measurement scenario and β_M is the molecular backscattering coefficient. From a priori analysis, the uncertainty on the backscattering coefficient is given by:

$$\Delta\beta_{tot}(z) = \sqrt{\sum_i \left(\frac{\partial\beta_{tot}(z)}{\partial X_i(z)}\Delta X_i(z)\right)^2}, \qquad (5)$$

where $X_j(z)$ represent respectively the arguments with their absolute uncertainty ΔX_j of the total backscattering function in Eq. (4).

The uncertainty in the NRB is given by:

$$\Delta P_{NRB} = \sqrt{\frac{[\delta P_{Raw}(z)]^2 + \delta B_{bkg}^2}{[P_{Raw}(z) - B_{bkg}]^2} + \left[\frac{\delta E}{E}\right]^2 + \left[\frac{\delta O}{O}\right]^2}. \qquad (6)$$

Using the Poisson statistics, the uncertainty for $P_{Raw}(z)$ is:

$$\delta P_{Raw}(z) = \sqrt{\frac{P_{Raw}(z)}{N}}, \qquad (7)$$

where N is the number of shot during the acquisition of the signal and is dependent of the data rate. N is equal to 600 for a 30 s data rate. Also the incertitude on B_{bkg} follows the Poisson statistic [2].

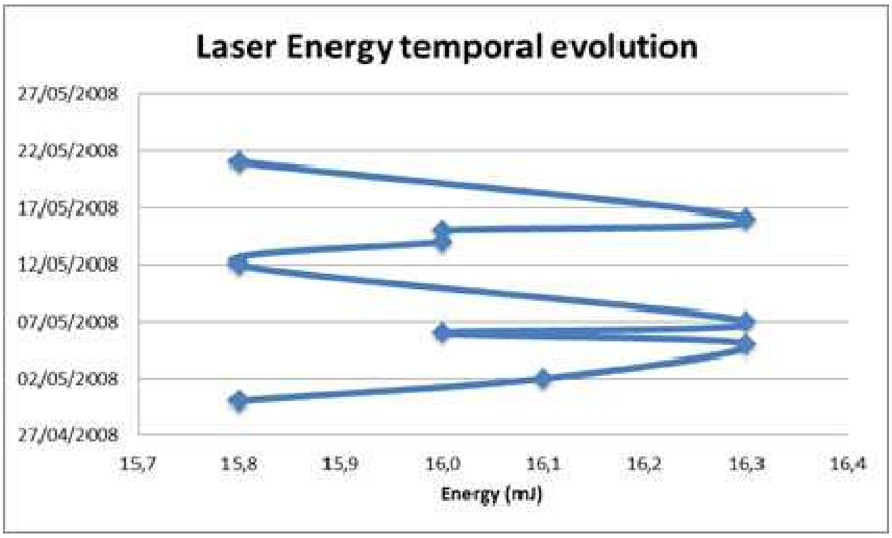

Fig. 1. Laser energy temporal evolution.

The corrections of detector dead-time effects could factor into the uncertainties in $P_{Raw}(z)$ and B_{bkg} and usually are no bigger than 1% overall the profile. Changes in the energy monitor value from pulse to pulse during the measurement period will produce uncertainty in the energy value. In Fig. 1 is represented the laser energy measurement over 26 days.

When the change in temperature is low, the main source of energy change is due just to the statistical fluctuation within the detector. Usually the energy error is not bigger than 3%. Full overlap is reached at about 150 m, so we consider this factor equal to the unity in this work.

If now it is retrieved the aerosol backscattering, it is possible to retrieve the uncertainty using the previous equations. As example, if 30 s data rate is assumed,

$$\delta P_{Raw}(z) = \sqrt{\frac{P_{Raw}(z)}{600}} \text{, and } \delta B_{bkg} = \sqrt{\frac{B_{bkg}}{600}}$$

while for energy variation we assume the worse case of 3% and either the factor dead-time of 1%. Once the particle backscattering uncertainty is determined, as reported in [3], we can proceed to evaluate the committed error in profile extinction and subsequent AOD.

From Klett algorithm [4] and the Lidar Ratio definition, we know that the particle extinction is:

$$\alpha_P = L_R \beta_P \, , \tag{8}$$

with relative absolute error:

$$\Delta\alpha_P = \sqrt{L_R^2 \Delta\beta_P^2 + \beta_P^2 \Delta L_R^2} \, . \tag{9}$$

Then, the particle AOD on entire column is by definition:

$$AOD = \int_0^{Zaer} \alpha_P(z')dz' = \sum_{i=1}^{i=i_{Zaer}} \alpha_p^i \Delta z \, , \tag{10}$$

where *Zaer* is the altitude at which backward Klett inversion starts [3]. The uncertainty in *AOD* determination is then the sum of the extinction uncertainties:

$$\Delta AOD = \sum_{i=1}^{i=i_{Zaer}} \Delta\alpha_p^i \, . \tag{11}$$

Through these procedures it is possible then to determine the uncertainties relative to the measured physical quantities. One among the dominant uncertainty sources is for sure the background light during daytime that lower the signal-to-noise ratio.

3. PBL validation campaigns

The Planetary Boundary Layer is the lowest part of the atmosphere that is directly influenced by the presence of the Earth's surface, and responds to surface friction about an hour or less [2]. Surface forcing includes frictional drag, evaporation and transpiration, heat transfer, pollutant emission and terrain-induced flow modification. The Boundary Layer thickness is variable in time and space, ranging typically from a few hundred meters up to 1-3 km depends on the nature of the surface (land or ocean) and on the meteorological conditions. Characterization and temporal evolution of the PBL is required to trace pollutants in large metropolitan areas.

EZ Lidar™ was deployed at LMD in Palaiseau, France to validate the PBL height estimation with those retrieved by the algorithm STRAT [5] from data acquired by the LNA. The 12-days measurement campaign shows (Fig. 2) a correlation between the instruments of 95% (for 5 minutes averaging).

In addition, the automatically retrieved Aerosol Optical Depth is compared in Fig. 3 with the sun-photometer data (P.Goloub, AERONET, France). Around noon, sun-photometer data were not available due to passing of sub visible clouds.

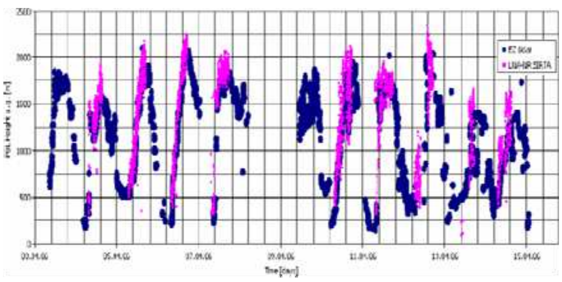

Fig. 2. PBL Height retrieval from EZLIDAR (blue) and STRAT (purple).

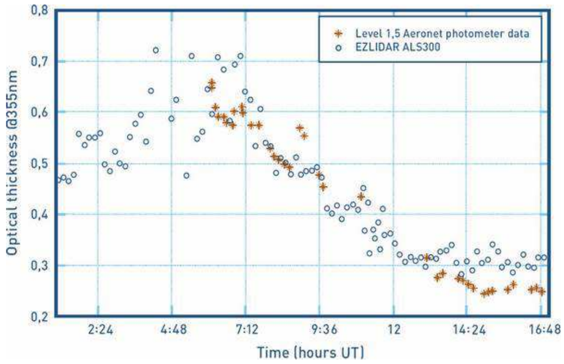

Fig. 3. Level 1.5 Aeronet sun-photometer data (crosses) AOD EZ Lidar™ retrieval (circles).

Moreover, Europe is conducting a pioneer project in order to constraint its Greenhouse gas emissions (CO2, CH4, N20,PFC,..), targeting 80% of carbon emission reduction within the next 40 years . The pilot project, named ICOS (Integrated Carbon Observation System), has been launched in order to create and maintain a coordinated, integrated, long-term high resolution network of atmospheric and ecosystem observations. During the initial platform design phase, several lidars were deployed nearby Orleans, France, to retrieve continuous PBL heights and aerosol structures. Under all weather conditions, clear sky, fog, low clouds, the EZ Lidar™ has been able to detect the different layers, residual, nocturnal and convective, from 75m up to 2km during the whole month of October 2008. Moreover, thanks to its 3D scanning capability, the EZ Lidar™ was able to provide the variability of the PBL height around the site as shown in Fig. 4, enabling the scientists to estimate the flux intensities that play a key role in the radiative transfer budget and in the atmospheric pollutants dispersion.

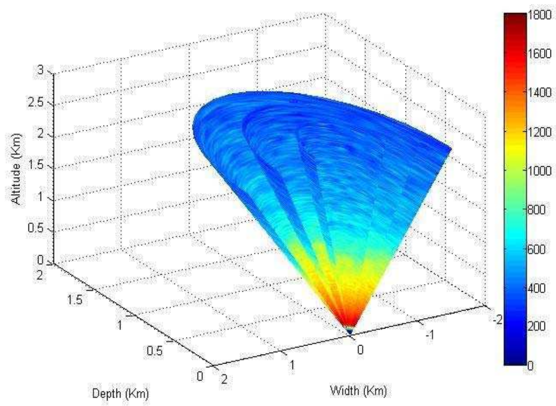

Fig. 4. Orleans 3D-PBL height measurements.

4. Validation campaign at ARM/SGP site

The objective of this campaign was to compare the performances of EZ Lidar™ instrument with those of Micro Pulse Lidar (MPL), deployed from some years at various sites in the framework of the MPLnet network by NASA. Raman Lidar (RL) measurements [7] are also available and they will be used as input of EZ retrieval algorithm to assess how large is the retrieval error. The intercomparison measurement campaign took place on 23rd and 24th October 2006 at Southern Great Plains, situated in Oklahoma, United States. SGP Central Facility coordinates are: N36° 37' W97° 30' with an altitude of 320 meters above sea level. Raman Lidar (RL) data measurements are available on 24th October. Raw data from MPL and EZ Lidar™ show for the first day clear atmosphere conditions, while on 24th October cirrus clouds between 10 and 12 km, alto stratus and cumulus are present during the day. Intercomparison took place from 5pm to 0am (UTC) on both days. Due to the different atmospheric conditions, both systems were completely analyzed under different features. Following plots show the NRB signal [6] as function of the time for EZ, MPL and RL. on 24th Oct).

MPL data are not separated into polarized components and are corrected with the overlap function; similarly also EZ Lidar™ data are corrected with the overlap function. Both instruments overlap functions are plotted in Fig. 6.

It can be noticed that, due to the extremely narrow MPL Lidar field of view, complete overlap is reached around 5 km, while EZ Lidar reaches it at 220 m (and 98% overlapping at 170m). A narrow field of view permits to reduce unwanted solar background and effects due to the multiple scattering, but presents less accuracy in the recovering region. The Signal-To-Noise Ratio (SNR) is a parameter to assess Lidar performances. For a given Lidar signal, being the received number of photons small enough to approximate the detected signal by a Poisson distribution, SNR can be retrieved using the following equation [5]:

$$SNR(z) = \frac{NP_{Raw}(z)}{\sqrt{P_{Raw}(z)N + NB_{bkg}}}. \qquad (12)$$

where N is the number of accumulated shots in 30s, $P(z)$ are the photoelectrons received from range z as in Eq. (1) and B_{bkg} is the received power due to the solar background. SNR profiles for EZ, MPL and RL instruments, as plotted in Fig. 7.

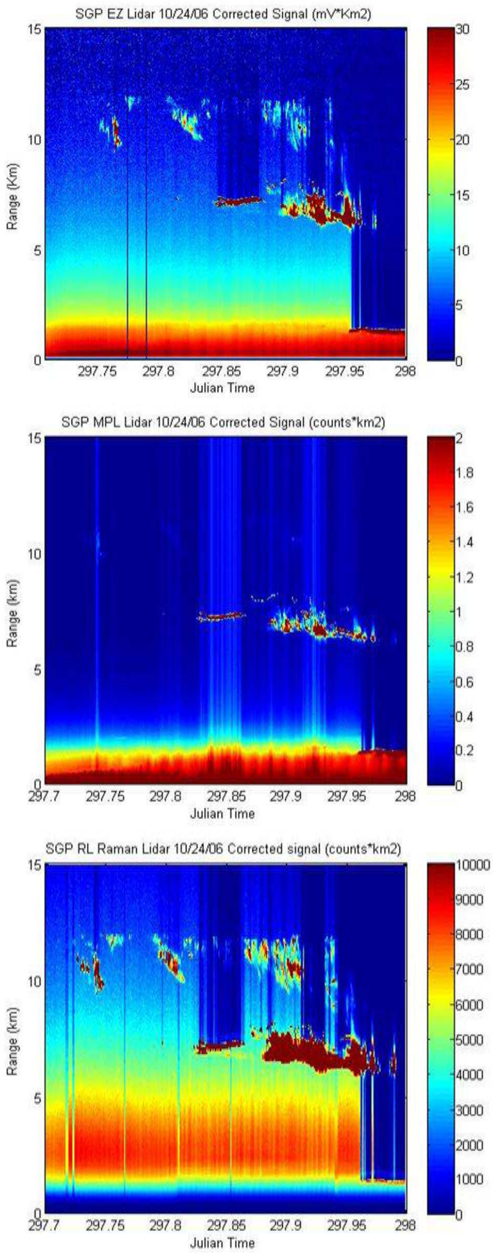

Fig. 5. Normalized Relative Backscatter (NRB) for EZ lidar (top), MPL lidar (middle) and RL Raman Lidar (bottom) on 24th October 2006. Reference time is in UTC.

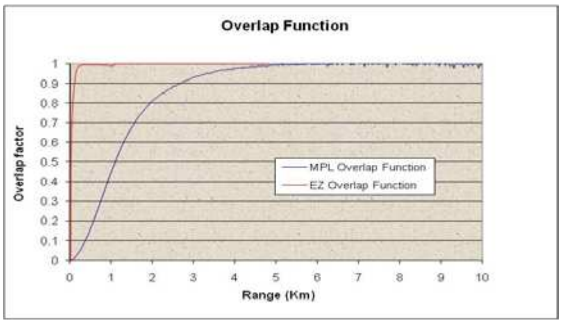

Fig. 6. EZ Lidar™ (red) and MPL(blue) overlap function.

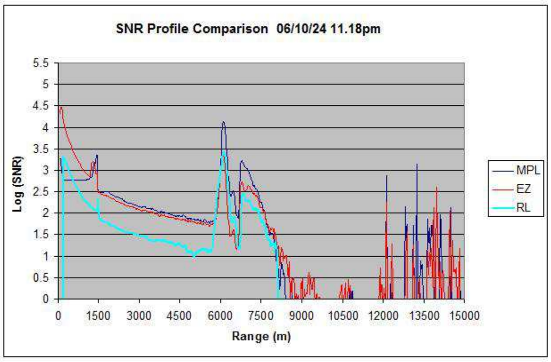

Fig. 7. EZ, MPL, RL signal-to-noise profiles on 24th Oct, 11.18pm (UTC)

It is interesting to notice that EZ Lidar™ SNR is better in the first 1.5 km and it is comparable further. This is a consequence of a lower EZ full overlap, as showed in Fig. 5. The results are schematically reported in Table II, where the lidar range is defined as the range at which SNR=1. Bias indicates the percentage divergence between the measured molecular signal and the normalized range corrected lidar signal.

Table II

Comparison result for 24th Oct, 11.18pm (UTC)

10/24.06 11.18 pm	EZ	MPL	RL
Lidar range	~9000 m	~8800 m	~8000 m
SNR10	~8500 m	~8500 m	~5000 m
Overlap	~320 m	~5000 m	n/a
Bias at 6 km	<20%	<15%	<55%

5. TIGER-Z NASA campaign

In 2008, the NASA Aerosol Robotic Network (AERONET) began a four-year project with regular intensive field campaigns, called TIGER-Z, to measure aerosol microphysical and optical properties over India. Collaborating entities in India include the Department of Science and Technology, Ministry of Earth Sciences, IIT Kanpur, IIT Kharagpur, and the Indian Space Research Organization (ISRO). India collaborators are currently holding campaigns on measuring the monsoon and thunderstorms over India: Continental Tropical Convergence Zone (CTCZ) and STORMS. The AERONET/CALIPSO campaign share existing resources (e.g., facilities, aircraft, and manpower) established for the ongoing India-sponsored campaigns and utilize instruments through other international partnerships among them with LEOSPHERE (France).

EZ Lidar™ was deployed at the Indian Institute of Technology, in Kanpur (26.45N, 80.23E), India, in the end of April 08. The EZ Lidar instrument was placed together with several sun photometers under the track path of the CALIPSO satellite. Measurements took place during three days from 28th April 08 to 1st May 08. Outside temperatures exceeded 45°C shadowed during these days.

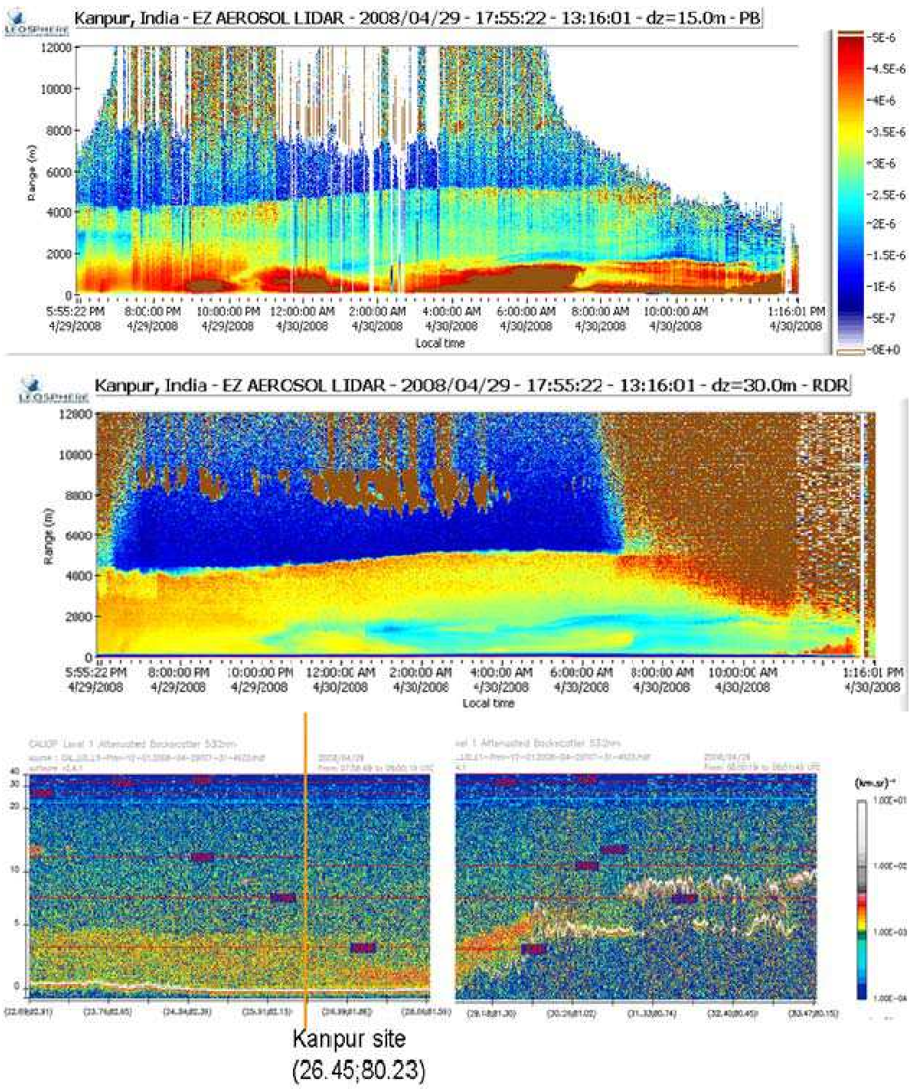

Fig. 8. EZ Lidar™ backscattering quicklook (upper), relative depolarization ratio (middle), CALIPSO Level 1 attenuated backscatter (lower).

In Fig. 8 is plotted EZ Lidar™ aerosol backscatter profiles retrieved on 29th-30th April 08 (upper); Relative Depolarization ratio(RDR) (middle) and CALIPSO level 1 Lidar attenuated backscatter coefficient (lower).

In the evening of 29th April, we observe two main layers up to 4km (Fig. 8, upper). Higher backscatter below 1.5km is found after 9pm on the 29th. The depolarization ratio is quite homogeneous in the two layers before 9pm, around 10-12%. After 9pm we start observing the creation of a new layer from the ground and up to 1.5km, with a DR between 4% and 8%, indicating a mix between pollution and dust.

In both EZ Lidar™ and CALIPSO satellite quicklooks, even if the time scale is different, we can observe the presence of a thick aerosol layer, up to 4km.

In Fig. 8 (lower) we also see an increase of the backscatter coefficient on the foothills of the Himalayas, either due to a change in the aerosol type, as biomass burning highly present during this season, or to a higher aerosol concentration. Depending on the air masses trajectories, coming from the North West on these days, these aerosols can be advected toward Kanpur in the lowest troposphere. That may explain the low DR values found in the EZLIDAR results after 9pm on April the 29th.

The retrieved EZ Lidar™ Aerosol Optical Depth (AOD) is validated against the in-situ co-located sun photometer. Measurement data run on 29th of April 08 from 10.15 pm to 12.00 am and on 30th April 08, from 6.28 am to 8.28 am (Local Time). By default the Lidar ratio has been set to 35 in the software. We compared AOD from the EZ Lidar™ and the AOD retrieved from the sun –photometer located at IITK. After an iterative process, we conclude that a mean LR of 50 sr on the 29th and of 90 sr on the 30th is more adapted for the inversion process of the lidar data. On 30th April 08 we have the results shown in Fig. 9.

The continuous curve is the AOD coefficient retrieved by the sun photometer. The white spots are the temporal evolution of the AOD retrieved by the EZ Lidar™. If we smooth and average the EZ AOD values, we have in this temporal interval a mean for the AOD of 0.56. The AOD average measurement value from the photometer is 0.56. The agreement between the instruments is very high. Resuming over different time intervals we have the results shown in Table III.

The total uncertainty is then the sum over the entire profile of the uncertainties on the extinction as calculated in paragraph 2. In this case ΔAOD=0.005.

This increase of the Lidar ratio between the 29th and 30th April from 50 sr to 90 sr (@355nm) indicates the evolution of the mean aerosol from a dusty coarse mode aerosol toward a more mixed aerosol of dust and small particles. This is correlated with the depolarization ratio results shown above, with an higher DR on the 29th and low DR values from 0 to 1.5 km on the 30th of April, due to more spherical particles like biomass burning or pollution.

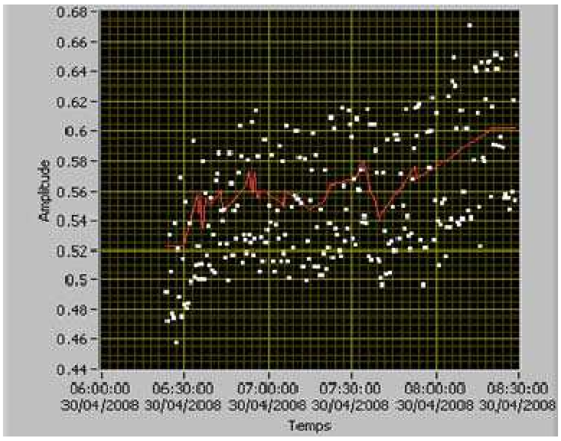

Fig. 9. AOD intercomparison. Red curve represent the temporal evolution of AOD measured by the photometer, while the white points represent the EZ Lidar™ measurements on 30th Apr. 08.

Table III

Results of AOD retrievals intercomparison between EZ Lidar™ and a co-located sun photometer

	29/04/2008	30/04/2008
Mean AOD sun photometer	0.51	0.56
Mean AOD EZLIDAR	0.51	0.56
Mean Lidar Ratio (sr)	50	89
STD L_R (sr)	20	22

5. Conclusions

The EZ Lidar™ instrument has been validated in several intercomparison campaigns, with different remote o in-situ instruments. PBL height retrieval shows a correlation of 95% with STRAT retrieval algorithm at LMD.

The analysis of the obtained results at ARM/SGP campaign shows that EZ lidar data quality is comparable with MPL data during daytime and under multi layered cloud conditions, and present a better maximum range under clear sky conditions. In these calculations, MPL data are referred to parallel polarization, while EZ data contain both.

Outdoor and unattended use capabilities of the EZLIDAR™ added to its measurements performances define then this instrument as a good candidate for deployment into growing global aerosol and cloud monitoring networks and research measurement campaigns.

